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S. Takeuchi, F. Myhrer and K. Kubodera  
Department of Physics and Astronomy, University of South Carolina,  
Columbia, SC29208

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# On the Spectacular Large Asymmetry in $\bar{p}p \rightarrow \pi^-\pi^+$ and $\bar{p}p \rightarrow K^-K^+$ Reactions

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## Abstract.

An illustrative analysis is presented to show the origin of the energy-independent maximal asymmetry observed for wide ranges of angles in the reactions  $\bar{p}p \rightarrow \pi^-\pi^+$  and  $\bar{p}p \rightarrow K^-K^+$ . The general nature of our simple relation between helicity -flip and -nonflip partial wave amplitudes enforces the notion that these features of the asymmetry for these two annihilation reactions are likely to persist within the hadronic regime. At higher energies these features of the asymmetry will probably be modified significantly, signaling the onset of perturbative QCD. Our study supports the arguments that the final  $\bar{K}K$  state originates from a more central reaction than the  $\pi\pi$  final state.

## 1 Introduction

The experimentally observed asymmetries  $A_{0n}$  in the annihilation reactions  $\bar{p}p \rightarrow \pi^-\pi^+$  and  $\bar{p}p \rightarrow K^-K^+$  seem to reach the maximal possible value of 1 over wide ranges of angles and  $p_{lab}$  between about 1 GeV/c and 2.2 GeV/c [1, 2, 3]. The reaction  $\bar{p}p \rightarrow \pi^-\pi^+$  has a very large  $A_{0n}$  for  $p_{lab} \gtrsim 1.5$  GeV/c, while the  $A_{0n}$  of the final  $K^-K^+$  state has values close to 1 for  $p_{lab} \gtrsim 1$  GeV/c. These remarkable features seem to call for a simple explanation. This explanation must simultaneously account for the following aspects of the observed differential cross sections: the  $d\sigma/d\Omega$  for the final  $\pi^-\pi^+$  reaction shows pronounced oscillations whereas that of the final  $K^-K^+$  reaction has a strong forward peak and a smooth backward plateau.

The angular oscillations of the  $d\sigma/d\Omega$  for  $\bar{p}p \rightarrow \pi^-\pi^+$  lead in an early model analysis to the speculation of the existence of possible J=3, 4 and 5 meson resonances [4], where it was assumed that one partial wave dominates at each energy. A recent partial wave analysis based on dispersion relation theory of the  $\bar{p}p \rightarrow \pi^-\pi^+$  reaction is not incompatible with "resonance activity" in some partial waves [5]. Our "geometrical" analysis [6] presented below does not require any explicit meson resonances and will reproduce in a natural way the observed behaviour of  $A_{0n}$  and  $d\sigma/d\Omega$ .

From the baryon-meson picture these reactions with two pseudo-scalar mesons in the final state are expected to be similar to each other. From a subnucleonic viewpoint they can be very different in nature because  $\bar{p}p \rightarrow K^-K^+$  involves the annihilation of two initial valence  $\bar{q}q$ -pairs accompanied by the creation of an  $\bar{s}s$ -pair, while  $\bar{p}p \rightarrow \pi^-\pi^+$  can take place simply by annihilating one  $\bar{q}q$ -pair. Which picture is more appropriate may depend on the energy. The angular dependence of the measured  $A_{0n}$  and  $d\sigma/d\Omega$  for the two reactions [1, 2] indicates that the "reaction mechanism" for  $p_{lab} \lesssim 1$  GeV/c is different from that of the higher energies. At these low energies the coupled-channels method with the explicit enumeration of possible hadronic channels may be a useful theoretical framework [7, 8]. As the incident energy increases, the coupled-channels method becomes more and more complicated; meanwhile, in the few GeV/c energy region, it is expected that we are still below the energy regime where perturbative QCD calculations are valid. The afore-mentioned maximum symmetry is seen at the higher end of the LEAR energies, and our studies so far [6] have focused on this energy region. At the AGS accelerator at Brookhaven National Laboratory and at the proposed *SuperLEAR* and *KAON* facilities we probably will reach energies where perturbative QCD calculations become relevant for exclusive hadronic reactions. For these higher energies, we expect that the observed maximum asymmetry phenomena *will break down*, signaling the onset of the perturbative QCD energy regime.

## 2 A Diffraction Model Analysis

Each of the reactions under consideration can be characterized by two independent helicity amplitudes:  $f_{++}$  (helicity non-flip) and  $f_{+-}$  (helicity flip). In terms of these two amplitudes the cross section and the asymmetry are given as

$$d\sigma/d\Omega = |f_{++}|^2 + |f_{+-}|^2 \quad \text{and} \quad A_{0n} = 2\Im m(f_{++}^* f_{+-}) / (d\sigma/d\Omega). \quad (1)$$

The partial wave expansion gives

$$f_{++} = \frac{1}{p} \sum_{J=0}^{\infty} (J + \frac{1}{2}) T_+^J P_J(\cos \theta) \quad (2)$$

and

$$f_{+-} = \frac{1}{p} \sum_{J=0}^{\infty} (J + \frac{1}{2}) / \sqrt{J(J+1)} T_-^J P_J'(\cos \theta) \sin \theta. \quad (3)$$

Conservation of parity and angular momentum implies that only tensor-coupled  $\overline{N}N$  partial waves ( $J = L \pm 1$ ) contribute to this reaction. We assume that  $T_-^J$  is given by the derivative of  $T_+^J$  w.r.t the scattering impact parameter  $b$  since we expect the helicity flip amplitude is most effective at the *interaction surface*:

$$T_-^J = \text{const. } \partial T_+^J / \partial b. \quad (4)$$

(A similar relation has been found phenomenologically in the corresponding  $t$ -channel process,  $\pi N$  scattering [9], as well as in  $\overline{p}p$  elastic scattering [10] in this momentum range.) Then, using  $J \approx pb$ , we find the basic “differential” relation,

$$T_-^J \propto \Delta T_+^J / \Delta J \quad (5)$$

or

$$\frac{J + \frac{1}{2}}{\sqrt{J(J+1)}} T_-^J = \frac{1}{\beta} (T_+^{J-1} - T_+^{J+1}). \quad (6)$$

where  $\beta$  is a constant parameter. This assumption leads to

$$f_{+-} = -\frac{1}{\beta} f_{++} \sin \theta \quad (7)$$

and

$$A_{0n} = \frac{2\Im m \beta}{|\beta|^2 + \sin^2 \theta} \sin \theta \quad (8)$$

With an imaginary  $\beta (= i)$ ,  $A_{0n}$  of eq.(8) will be larger than 0.9 over a very wide angular range ( $|\cos \theta| \sim 0.8$ ) whereas  $d\sigma/d\Omega$  may have a significantly stronger angular dependence, determined by  $f_{++}(\theta)$ . (We can show in a DWBA- type calculation that  $\beta$  is almost constant as a function of  $\theta$  [6].)

Since so many competing annihilation channels are open at the energies under discussion, we initially assume as an explicit model example that the amplitudes are given by “classical” grey- or black-sphere amplitudes. These amplitudes will give  $A_{0n} \approx 1$ .

$$T_+^J = \begin{cases} B \exp(-aJ) & (J \leq J_{max}) \\ 0 & (J \geq J_{max}) \end{cases} \quad (9)$$

where  $B$  and  $a$  are constants. To reproduce the observed  $d\sigma/d\Omega$  for  $\overline{p}p \rightarrow \pi^- \pi^+$  we need  $a \approx 0$  and  $J_{max} = 4$ . This is a “black” sphere amplitude of radius equal to  $J_{max}/q$ . For the reaction  $\overline{p}p \rightarrow K^- K^+$  data requires  $a \approx 0.5$  corresponding to a “grey” sphere. This means the lowest partial waves ( $J=0$  and 1) dominate in this reaction. As a consequence we conclude that the  $\overline{p}p \rightarrow \pi^- \pi^+$  reaction occurs over a larger interaction volume than the  $\overline{p}p \rightarrow K^- K^+$  reaction [6].

### 3 Discussion and Conclusions

We have also studied this problem using a DWBA approach [6] to further examine the assumption of the phenomenological analysis above. The optical potential for the initial  $\bar{N}N$  channel should reflect the strong  $\bar{N}N$  absorption for the low impact parameter region. This implies that the low partial wave amplitudes are close to their unitarity limit. We also expect strong absorption effects from the final-state  $\pi\pi$  and  $\bar{K}K$  interactions. However, because the final state interaction is not well known at these high energies, we parametrize the effective transition operator that simulates the combined effects of the final state interaction and the transition operator.

Our study [6] indicates:

1. The strong angular dependent cross section and the smooth angular asymmetry can be reproduced simultaneously with the use of a simple transition operator potential. This potential must be a sum of two terms of very different ranges.
2. The interference term arising from the sum of the two transition potentials (interference of the final state interaction and the annihilation reaction?) is essential to yield the large asymmetries. This is consistent with the findings at low energies ( $p_{lab} \lesssim 1$  GeV/c) [8];
3. The resulting behaviour of the "effective"  $\beta$  (see eq.(8) of the diffraction model) is found to be almost independent of angle  $\theta$  and dominantly imaginary.
4. The initial state distortion due to our  $\bar{N}N$   $L \cdot S$  potential plays a minor role in explaining  $A_{0n}$ . (Since it is tensor coupled  $\bar{N}N$  partial waves which contribute to these reactions we should have used  $\bar{N}N$  tensor forces to generate the initial  $L \cdot S$   $\bar{N}N$  amplitudes.
5. As stated the  $\bar{p}p \rightarrow K^-K^+$  reaction takes place at much shorter distances than the  $\bar{p}p \rightarrow \pi^-\pi^+$  reaction. This result lends support to the arguments based on an analogy with QED [11] that the larger the number of initial  $\bar{q}q$  valence pairs which need to be annihilated for a specific  $\bar{N}N$  annihilation reaction to occur, the more central is the reaction.

Since our explanation [6] of the maximal  $A_{0n}$  is based on a rather general picture, we expect that the maximal  $A_{0n}$  will persist as the incident  $\bar{p}$  energy increases. Judging from the success of a similar diffraction model analysis for the  $\pi N \rightarrow \pi N$  scattering data for  $p_{lab}$  between 2 and 6 GeV/c [9], our description is presumably valid in a similar energy range. However, as discussed by Carlson *et al.* [12, 13], we do expect our scheme based on the hadronic picture to break down at higher energies when the perturbative QCD regime of exclusive hadronic reactions is reached. The onset of the perturbative QCD regime may be signaled by a significant change in the energy and angular variation of the asymmetry. Therefore the measurement of  $A_{0n}$  for  $p_{lab} > 2$  GeV/c is expected to be extremely useful not only for a better understanding of the nature of the extraordinarily large asymmetry observed in the LEAR energy region, but also for monitoring the possible onset of perturbative QCD.

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